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Two theropod track assemblages from the Jurassic of Chongqing, China, and the Jurassic Stratigraphy of Sichuan Basin

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Abstract　Four Jurassic dinosaur tracksites have been reported from Chongqing Municipality. These include the Lower Jurassic Dazu site in the Zhenzhuchong Formation, which yields the oldest sauropod trackway known from China. Two of the remaining three sites (Nan'an, and Jinji sites), variously regarded as Middle and Upper Jurassic, are here described in detail for the first time and regarded as Upper Jurassic, both from the Shangshaximiao Formation. The fourth site (Chengyu), so far not accessible to the present authors, is not described. The Nan'an site, and type locality of *Chongqingpus nananensis*, has yielded a large sample of theropod tracks from the heart of Chongqing Municipality, at a site that has been lost in the urban development. Fortunately the sample is preserved at Chongqing Museum of Natural History and has been studied independently on two occasions to produce the results presented here. *C. nananensis* is a medium-sized track (mean track length ~29 cm) that may best be accommodated in ichngenus *Kayentapus*, and may in some cases preserve ill-defined hallux traces. Associated tracks are attributed to cf. *Anomoepus*. Other smaller ichnospecies from other localities outside Chongqing municipality, and from older middle Middle Jurassic formations, were previously assigned to ichnogenus *Grallator*. The Jinji site has yielded a single long theropod trackway of a robust form tentatively labeled cf. *Therangospodus*. This Jinji trackway also provides intermittent evidence of a hallux. Although theropod tracks are becoming increasingly well-known in the Jurassic sections of Chongqing Municipality, the Sichuan Basin and the broader region, determining their precise age and assigning them to valid ichnotaxa remain challenging. This is because Jurassic theropod tracks,

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despite being abundant, show a continuous range of morphological, and preservational variation that is difficult to define and differentiate in space and time.

Key words Chongqing Municipality, Sichuan Basin, Late Jurassic, theropod tracks, ichnotaxonomy

1 Introduction

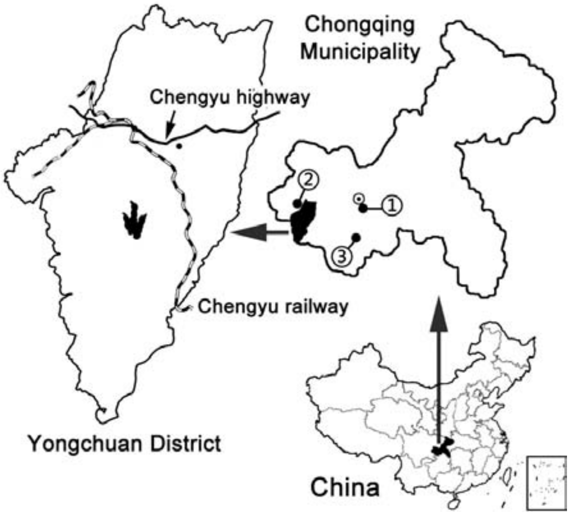

Fig. 1 Geographic position of the Jinji dinosaur footprint locality (indicated by the footprint icon)
Other three sites from Chongqing Municipality: ① Nan'an tracksite; ② Dazu tracksite; ③ Lotus tracksite

Chongqing Municipality is located in the southeastern corner of Sichuan Basin. The Middle Jurassic Sauropoda-*Shunosaurus* Fauna and Upper Jurassic Sauropoda-*Mamenchisaurus* Fauna were discovered in the Zigong area, Sichuan Basin (Peng et al., 2005). Famous dinosaur genera described from Chongqing Municipality include the theropod *Yangchuanosaurus* (Dong et al., 1978, 1983), the sauropod *Mamenchisaurus* (Young and Zhao, 1972), and the stegosaur *Chungkingosaurus* (Dong et al., 1983). In 2004, the Chongqing Museum of Natural History uncovered new sauropod skeletal materials in the Chongqing downtown area (Chen and Wang, 2005).

However, in addition to important dinosaur skeletal remains, abundant Jurassic dinosaur tracks have also been discovered in Chongqing Municipality, including four major tracksites (Fig. 1): 1) the Early Jurassic Dazu tracksite in the Zhenzhuchong Formation (Yang and Yang, 1987; Lockley and Matsukawa, 2009); 2) the Late Jurassic Nan'an tracksite in the Shangshaximiao Formation (Yang and Yang, 1987); 3) the Late Jurassic Chengyu Railway (Yongchuan section) tracksite in the Shangshaximiao Formation (Zhou C Y, pers. comm.); 4) the Late Jurassic Jinji tracksite in the Shangshaximiao Formation. In this paper, we discuss two tracksites (Nan'an tracksite and Jinji tracksite) in Chongqing municipality. Special attention is given to the Nan'an and Jinji tracksites, which have not previously be described in detail. As a geographic area, Chongqing Municipality forms a small part of the Sichuan Basin, which contains other track-bearing formations in addition to those discussed herein (Fig. 2).

The Lower Jurassic Dazu tracksite in the Zhenzhuchong Formation, first reported by Yang and Yang (1987) and later noted by Matsukawa et al. (2006), was briefly described by Lockley and Matsukawa (2009: fig. 7) to show what may be the oldest sauropod trackway known from China. The Nan'an tracksite was discovered in 1983 when a piece of theropod trackway was found along the southern bank of the Yangtze River by the Chongqing Sea-route Bureau during the course of building repair. These theropod tracks, originally described by Yang and Yang (1987), were entirely removed from the field into the museum collections and restudied independently by two teams from among the present authors (see below).

In 2010, a second occurrence of dinosaur tracks was discovered in Nan'an by Zhou Chang-Yuan, a farmer from Huanggua Mountain Village, Yongchuan District, Chongqing. In 2011, the senior author was invited by the Yongchuan District Administration Institute of Cultural Relics and Preservation to study the Yongchuan dinosaur tracks. Lastly, the Jinji site, discovered in Yongchuan District is here described in detail for the first time.

Institutional abbreviations CU. University of Colorado, Denver; JJ. Jinji tracksite, Yongchuan District, Chongqing, China; V (also CFNY, CFZW). Chongqing Museum of Natural History, Chongqing, China; ZLJ. World Dinosaur Valley Park, Yunnan, China.

2 Geological setting

2.1 Jurassic stratigraphy of the Sichuan Basin

As noted by Lucas (2001:122) "the Sichuan Basin contains Early, Middle and Late Jurassic vertebrate faunas in a 3000+ meter thick sequence of directly superposed" red bed fluvial and lacustrine strata that comprise at least nine formations. Lucas identified four formations as Lower Jurassic (Zhenzhuchong, Dongyuemiao, Maanshan, and Daanzhai formations), three as Middle Jurassic (Xintiangou, lower Shaximiao [=Xiashaximiao], and upper Shaximiao [=Shangshaximiao] formations), and two as Upper Jurassic (Suining and Penglaizhen formations). When Peng et al. (2005) was arranging the dinosaur fauna in the Zigong area, based on vertebrate fossils, a new stratigraphical sequence was adopted (Fig. 2). This scheme identifies two formations (Zhenzhuchong and Ziliujing) as Lower Jurassic, two (Xintiangou and Xiashaximiao) as Middle Jurassic and three (Shangshaximiao, Suining and Penglaizhen) as Upper Jurassic. In contrast to this new scheme, Matsukawa et al. (2006) and Chen et al. (2006) considered the Shangshaximiao Formation as Middle Jurassic, or even partly as Lower Jurassic, based on *Eubrontes*-*Grallator*-*Anomoepus* assemblages. At the 8th international congress on the Jurassic system in 2010, Wang et al. (2010) considered the Shangshaximiao Formation as Middle Jurassic, based on invertebrate fossils. It is not possible to decide the age of these formations only on the basis of tridactyl tracks. Herein we follow Peng et al. (2005) to take vertebrate fossils as a useful framework for our discussion of Chongqing ichnofaunas and comparison with the larger region of the Sichuan basin. However, we acknowledge that the stratigraphic schemes and age estimates of various workers differ in many details. As noted by Yang and Yang, 1987; Matsukawa et al., 2006; Lockley and Matsukawa, 2009, there are a number of track-bearing formations in the Sichuan Basin, useful

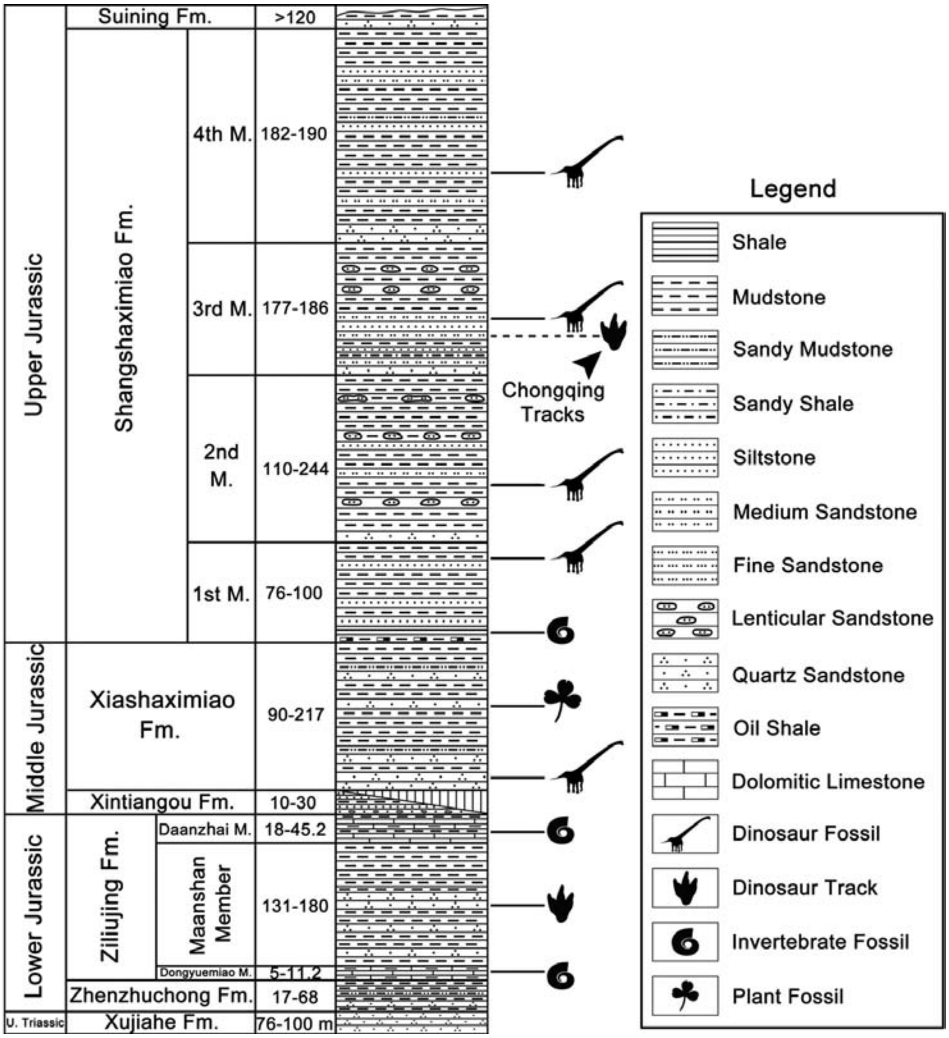

Fig. 2 Jurassic stratigraphy of the Sichuan basin after Peng et al., 2005

for comparative ichnology, even though they have not yielded significant tracksites in the more restricted geographical area of the Chongqing Municipality.

2.2 Zhenzhuchong Formation

The basal Jurassic Zhenzhuchong Formation was, according to Dong et al. (1983), formerly a member of the Ziliujing "Group" or "Ziliujing Beds" (*sensu* Tan and Li, 1933), which were subdivided into the Zhenzhuchong clays, Dongyuemiao limestones, Fenbao clays, Guojiaao sandstones, Maanshan clays, Daanzhai limestones, and Lianggaoshan sandstones (see Yi, 1958[1)] for similar subdivisions). Lucas (2001) recognized the Dongyuemiao, Maanshan,

1) Yi D T(易大同), 1958. Eastern Sichuan Ziliujing and Chungking groups. In: Report of Oil and Gas in Continental Jurassic Strata of Sichuan Basin (Eastern)(四川盆地(东部)侏罗系陆相地层及油气研究总结报告). 1–113(in Chinese)

and Daanzhai formations within the Ziliujing Group. A Jurassic age for the Ziliujing Group based on bivalve biostratigraphy was confirmed by the first discovery of Early Jurassic *Lufengosaurus* (prosauropod) Fauna elements in Zhenzhuchong beds. This, in turn, led to the elevation of the unit to formational status. According to Dong et al. (1983), the Zhenzhuchong vertebrate fauna include the prosauropod "*Gyposaurus*" *sinensis* and *Lufengosaurus* sp., and *Sinosaurus* sp. (called a poposaur by Dong et al. 1983 but actually a tetanuran theropod dinosaur), but Chen et al. (2006) reported "*G*." *sinensis* and *Sinosaurus* only from the laterally equivalent Lufeng Formation. However, Chen et al. (2006) also noted bivalve and plant fossils occurrenced in the Zhenzhuchong Formation and similarly ascribed it to Early Jurassic age. Palynological studies in the unit placed it in the *Cyathidites undulatisportes* zone, which is also regarded as Early Jurassic (Bai et al., 1983); plant fossils have also been used to assign the Zhenzhuchong Formation earliest Jurassic age (Liu et al., 2009). According to Gao (2007), the ichnotaxon *Weiyuanpus zigongensis* also originates from the Zhenzhuchong Formation. *Weiyuanpus* is probably a junior synonym of the more widespread theropod ichnotaxon *Eubrontes* (Lockley and Matsukawa, 2009; Lockley et al., 2013).

2.3 Ziliujing Formation

According to Lucas (2001), the Ziliujing Group makes up the remainder of the Lower Jurassic succession above the Zhenzhuchong Formation, and is divided into the Dongyuemiao, Maanshan, and Daanzhai formations. However, early at the Mesozoic Stratigraphy Session of the Three Provinces of Southwest China in 1974, according to the opinions of the majority, the former Ziliujing Group, Ziliujing Unit were replaced by the Ziliujing Formation and subsequently the Ziliujing Formation was divided into the Dongyuemiao, Maanshan, and Daanzhai members (Peng et al., 2005). The new names are now generally cited. Other remarkable dinosaurs including prosauropods, cf. *Lufengosaurus* from Zigong (Dong, 1984) and the primitive sauropod *Gongxianosaurus* from Gongxian, Sichuan Province (Wang and Zhou, 2005) simultaneously appeared in this formation.

Not many tracks have been reported from the Ziliujing interval, but according to Matsukawa et al. (2006), small grallatorid tracks in the Zigong Dinosaur Museum originate from the Ziliujing Formation (from Gongjing District, Zigong area). Xing (2010) reported extensive parallel sauropod trackways and scattered theropod tracks from Gulin, Sichuan Province, which are under the further study.

2.4 Xintiangou Formation

The Xintiangou Formation is the lowest of three units designated as Middle Jurassic by Lucas (2001). A number of tracksites have been reported from this unit, including Wumacun village sites A and B, respectively referred to as sites 20 and 21 in Matsukawa et al. (2006). Site A is the type locality for the ichnotaxa *Zizhongpus wumanensis*, *Tuojiangpus shuinanensis*, *Chonglongpus hei*, and *Chuanchengpus wuhuangensis*, and site B is the type locality for *Megaichnites jizhaishiensis* and *Chongqingpus microiscus*, all of which were described by Yang and Yang (1987), the *C. microiscus* is a *Grallator*-like ichnospecies (see Lockey et al., 2003). However, the validities of these ichnotaxa have been called into question by various authors (Gierliński, 1994; Lockley et al., 2003; Lockley and Matsukawa, 2009; Lockley et al., 2013). The Nianpanshan site (no. 25 in Matsukawa et al., 2006), another site in Xintiangou Formation, is, according to Yang and Yang (1987), the type locality for *Jinlijingpus nianpanshanensis*. This dubious ichnospecies is another likely synonym of *Eubrontes*. Lockley and Matsukawa (2009) presented a map of this site, which produced the first *Anomoepus* trackways reported from China.

2.5 Xiashaximiao Formation

The former Shaximiao Formation is widely exposed in the Sichuan Basin, and includes interlaced strata with uneven thicknesses of fuchsia mudstone, shale, and yellow-gray and purplish-gray arkosic sandstone. The large lenticular sandstone bodies vary in thickness from 650–2500 meters (Gu and Liu, 1997). The Shaximiao Formation is currently divided into the Middle Jurassic Xiashaximiao ("xia" = lower) Formation and the Upper Jurassic Shangshaximiao ("shang" = upper) Formation because of the large thickness and monotonous lithology (Compiling Group of Continental Mesozoic Stratigraphy and Palaeontology in Sichuan Basin of China, 1982). The Xiashaximiao Formation produces the *Shunosaurus* fauna, and the Shangshaximiao Formation produces the *Mamenchisaurus* fauna (Peng et al., 2005). According to Lucas (2001), the Lower and Upper Shaximiao formations are both Middle Jurassic in age. However, this suggestion is controversial. The dispute focused on the age of the Shangshaximiao Formation; whereas the age of the Xiashaximiao Formation pertaining to the Middle Jurassic is basically uncontroversial. Evidences supporting a middle Jurassic age for the Xiashaximiao Formation include: bivalves (Ma, 1984), conchostracans (Li et al., 2009), ostracods (Wang et al., 2010), spore and pollen (Wang et al., 2010), dinosaurs (Peng et al., 2005). All the above-mentioned fossil associations exhibit typical characteristics of the Middle Jurassic.

2.6 Shangshaximiao Formation

The Shangshaximiao Formation is the most widely distributed red strata in the Sichuan Basin, rich in dinosaur and other vertebrate fossils. The age of the Shangshaximiao Formation is disputed among geologists and paleontologists. Some paleontologists believe that the Shangshaximiao Formation pertains to the Middle Jurassic, based on plant fossils (Sze and Chow, 1962), bivalves (Gu et al., 1976), gastropods (Pan, 1980) and pollen assemblages (Wang et al., 1976; Wang et al., 2010). Whereas vertebrate paleontologists consider that the Shangshaximiao Formation pertains to the Late Jurassic (Dong et al., 1983; He, 1984; Li et al., 1999; Zhang and Li, 2003; Peng et al., 2005). Peng et al. (2005) considered the strata containing the famous *Mamenchisaurus* fauna differs significantly from the *Shunosaurus* fauna in the Xiashaximiao Formation because the genera and evolution level of sauropods coincides with the Late Jurassic Morrison Formation in the west of North America and the Late Jurassic Tendaguru Formation in Tanzania. Similar phenomena were inferred for large theropods and stegosaurs. Additionally, the vertebrate fossils (especially mamenchisaurs) discovered in the Shangshaximiao Formation are similar to the vertebrate fossils from the Late Jurassic Shishugou Formation (Jia et al., 2009) at the Junggar Basin, Xinjiang, China. For these reasons, the Shangshaximiao Formation is herein assign to the Upper Jurassic.

2.7 The age of Jinji and Nan'an tracksites

The Jinji tracksite is located on the slope of Huanggua Mountain, Jinji Ridge residents' association, Huanggua Mountain Village, southern suburb of Yongchuan District, Chongqing (Fig. 1). The tracks are preserved in the purplish-gray sandstone of the middle Shangshaximiao Formation. Neither ripple marks nor mud cracks are observed on the track-bearing surfaces.

The Nan'an tracksite is located within the city of Chongqing, near the Fifth People's Hospital in Tushan Road, Nan'an District. The Nan'an tracksite outcrop was first attributed to the Xiashaximiao Formation by Yang and Yang (1987), but was later recognized as an exposure of the Middle Jurassic middle Shangshaximiao Formation (such as Wu et al., 2003; Liu et al., 2006). Based on discussion in the previous section the Shangshaximiao Formation should be considered as Upper Jurassic. Most importantly, the lithological characteristics of Nan'an tracksite are the same as other dinosaur fossil sites referred to the Upper Jurassic Shangshaximiao Formation (Chen Wei personal observation), such as *Yangchuanosaurus shangyouensis* (Dong et al., 1978) and unnamed sauropod (Chen and Wang, 2005). As noted below, the common track types from this unit at the Nan'an site resemble *Kayentapus* and *Anomoepus*, which are characteristic of the Lower Jurassic, especially in North America where they are abundant. However, such tracks are known in younger Upper Jurassic in some areas such as Spain (Lockley et al., 2008) and so cannot be considered reliable as age indicators. More work is needed on the study of the Jurassic of the Sichuan Basin to establish both the precise age of formations and the distribution of well-defined footprint ichnotaxa. Also, while classic Lower Jurassic *Grallator*-*Eubrontes*-*Kayentapus*-*Anomoepus* ichnofaunas are 'typical' of the Lower Jurassic the extent to which elements are found in younger strata in Asia or other regions is poorly known, and it is already established that assemblages dominated by *Grallator* and *Grallator*-like species extend into the Cretaceous of Asia (e.g., Matsukawa et al., 2006).

3 Description of Chongqing Municipality tracksites

Although it is important to understand the relationship of all the Jurassic Sichuan Basin tracksites in order to place the Chongqing Municipality sites in context (see Discussion, below), our main focus here is to describe the younger tracksites from the Upper Jurassic Shangshaximiao Formation.

3.1 Theropod tracks from the Nan'an tracksite

3.1.1 The *Chongqingpus nananensis* type locality

The Nan'an tracksite, from the middle Shangshaximiao Formation in the heart of Chongqing Municipality, was first reported by Yang and Yang (1987), who named *Chongqingpus nananensis* from this site. They produced a map of the site (Yang and Yang, 1987: fig. 8; reproduced here as Fig. 3) and noted a few sedimentary features, such as ripple marks at the southern margin of the trackway. However, these features have been destroyed by subsequent urban development. The site is referred to by Matsukawa et al. (2006) locality 19 and reported as being in the Xiashaximiao Formation, at variance with the younger middle Shangshaximiao Formation designation proposed here (Wu et al., 2003; Liu et al., 2006).

In 2001, the site was visited by three of us (MGL, JL, and MM), but no track-bearing outcrops were found. However, we studied specimens from the site preserved in the Chongqing Museum of Natural History. Eight theropod tracks of similar morphology and size, in the series V1394, were traced (CU tracings 581 and 582: Fig. 4), and one (V1394-4) was replicated (now cataloged as CU 178.7). Additionally, we recorded a series of seven smaller tracks in series V1395 (excluding V1395-4 and V 1395-8, Fig. 5), all but the first of which (a small theropod track) appear to be poorly preserved *Anomoepus* tracks. Three of these, which show pes hallux traces (Fig. 5), were previously illustrated by Lockley and Matsukawa (2009: fig. 6C). Replicas of V1395-7 and 1395-9 are preserved as CU 178.8 and CU 178.9, respectively, and the series is recorded as CU tracing 583.

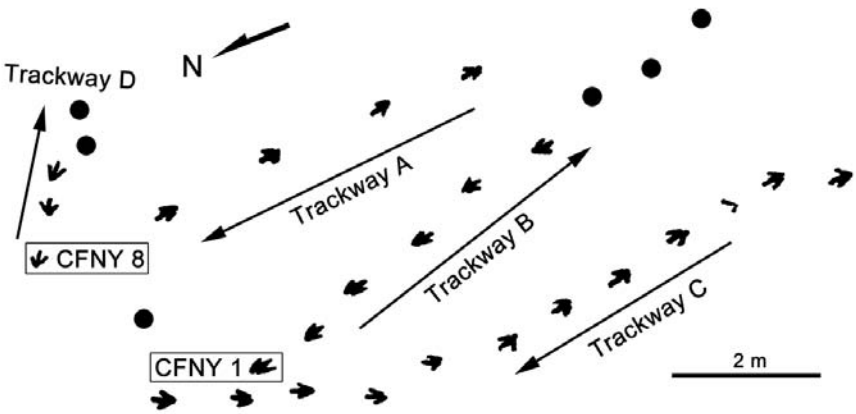

Fig. 3 The trackways of *Chongqingpus nananensis* from Nan'an tracksite, Chongqing, China
Based on Yang and Yang, 1987: fig. 8; black circle indicates the indistinguishable tracks in the original illustration. Trackway A–C are similar in individual track size and morphology, referred to *C. nananensis*; Trackway D individual tracks are considerably small, referred to *C. yemiaoxiensis* (Yang and Yang, 1987)

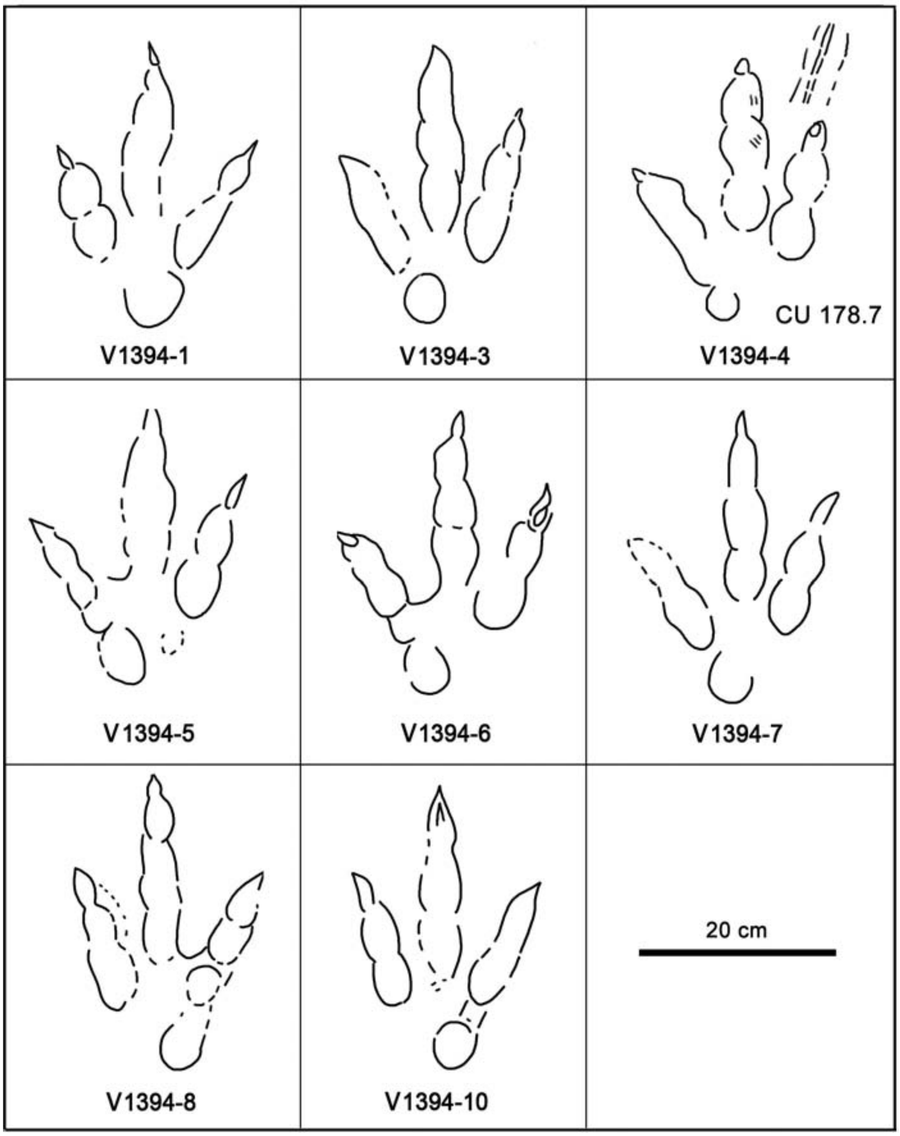

Fig. 4 Eight *Chongqingpus nananensis* from the V1394 series (excluding V1394-2 and 1394-9), all represent tridactyl theropod tracks of similar size with typical 2-3-4 digital pad formulae corresponding to digits II, III and IV respectively

A replica of V1394-4 is preserved as CU 178.7. Compare with Fig. 6. The outline drawings of V1394-5 and V1394-6 have minor differences between Fig. 4 and 7, the reason was these specimens have been studied independently on two occasions to produce the results presented here. The drawing of fig. 7 has shown more delails, indicating more thorough research was conducted in 2012

The Third National Archaeological Survey (July 2007–December 2011) found that the Nan'an tracksite had been destroyed or obscured by urban construction, as noted previously when the 2001 team attempted to relocate the site. The only accessible specimens of *C. nananensis* and *C. yemiaoxiensis* are those previously collected by the Chongqing Museum of Natural History. The lead author (LX) re-investigated *C. nananensis* (V1401 [(former specimen number: CFNY 1; Fig. 6 herein)]; V1394-5, V1394-6; Figs. 4 & 7 herein); and other two authors (LJ and CW) also re-investigated *C. yemiaoxiensis* (V1395-2 C1055), and *C. microiscus* (V1400 C1062, former specimen number: CFZW 176). These specimens have been assigned new specimen numbers because the older specimen numbers were lost. Correlating these specimens with previous descriptions has been accomplished via comparisons with the pictures provided by Yang and Yang (1987), which are labeled with the original specimen numbers. The advantage of two investigations of the collection by two separate teams at different times (2001 and 2007-2011) is to produce two separate, independent analyses (compare Figs. 4 and 5 with Figs. 6 and 7).

Abundant other trace fossils are also observable on the trackway bedding plane near the dinosaur tracks (Figs. 6-7). Many of these trace fossils are similar to *Planolites* in overall

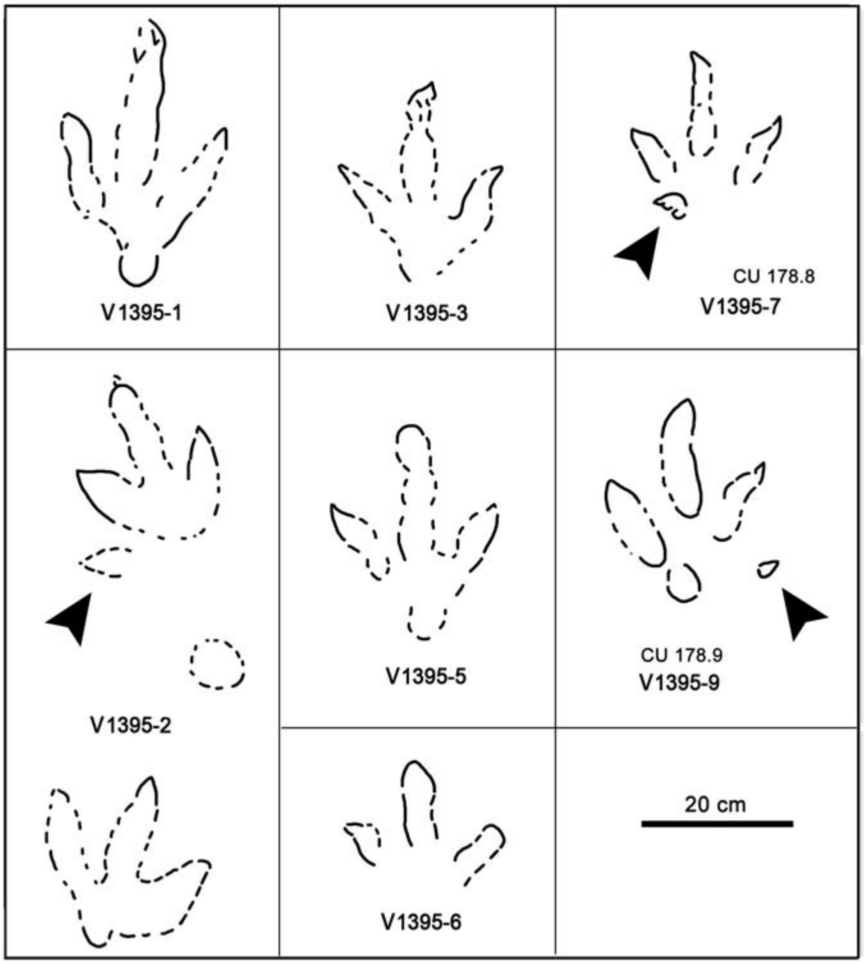

Fig. 5 Seven tridactyl and tetradactyl tracks from the V1395 series (excluding V1395-4 and V1395-8) V1395-1 appears to be of theropod affinity, the others are tentatively attributed to *Anomoepus* (cf. Lockley and Matsukawa, 2009: fig. 6C). Replicas of V1395-7 and 1395-9 are preserved as CU 178.8 and CU 178.9 respectively. Arrows point to digit I impressions

morphology, but are linear instead of sinuous. Vague, meniscate, backfilled burrows assignable to *Ancorichnus* are also observed. This trace fossil assemblage likely represents the work of insects and insect larvae, most likely burrowing beetles (Hasiotis, 2002). The presence of *Ancorichnus* indicates either crevasse-splay deposits on a deltaic plain (Li et al., 1997) or a floodplain environment (Frey et al., 1984).

3.1.2 The status of the type material of *Chongqingpus nananensis*

The type specimen of *Chongqingpus nananensis*, CFNY 1, became mired in some confusion because the line drawing of CFNY 1 in Yang and Yang (1987: fig. 9) and the specimen photo in Yang and Yang (1987: plate III-2) are mismatched. The most probable situation is that Yang and Yang (1987) mislabeled plate III-2 (which refers to the holotype CFNY 1) and plate III-3 (which refers to the paratype CFNY 4), when in fact the reverse is correct: i.e., the holotype CFNY 1 is in fact illustrated in plate III-3 (not plate III-2). This corrected arrangement means that the photograph of the holotype (CFNY 1) matches fig. 9 (in Yang and Yang, 1987) and shows the purported hallux trace, not seen in paratype CFNY 4. This interpretation is also confirmed by finding that the specimen illustrated in Yang and Yang (1987, plate III-3) actually bears the holotype number (CFNY 1), although confusingly it also has the new specimen number V1401 (Fig. 6).

Yang and Yang (1987) did not provide a line drawing of CFNY 4. However, CFNY 4 had been replicated, and casts of the specimen were sent to various other Chinese museums. In 2011, the lead author (LX) examined one of the CFNY 4 casts (Fig. 7E) at the World Dinosaur Valley Park, Lufeng County, Yunnan Province (cast number: ZLJ T1), and it appears to be a replica of CFNY 4 (compare Fig. 7E herein with plate III-2 in Yang and Yang, 1987).

The type track CFNY 1 (V1401) was illustrated both as a stylized line drawing (Yang and Yang, 1987: fig. 9) and as a photograph. However, the tracing we obtained from the cast is somewhat different (Fig. 6). The impression of digit II is close to that of digit III, more or less as shown by Yang and Yang (1987), but the space between digit II and digit III is slightly larger than that between digit III and digit IV impressions, unlike the depiction of Yang and Yang (1987). There are also differences in how Yang and Yang (1987) depicted the border and interval between the metatarsophalangeal pad of digit IV and the other three pads of digit IV. The substantial sample of topotypes of *C. nananensis* (Fig. 4) consistently shows the metatarsal phalangeal pad (pad 1) to be more clearly separated from pads 2-4 than shown by Yang and Yang (1987). However none of the tracks in the topotype sample (Fig. 4) were interpreted as showing hallux traces, and because the holotype was not available to the 2001 team, no evidence of a hallux was inferred. This raises the question of whether any tracks, including the holotype (CFNY 1 =V1401) and paratype (CFNY 4= ZLJ T1), truly have a hallux. As noted below, these two specimens have features that could be interpreted as hallux traces, despite the fact that they are not common in the sample as a whole. As discussed below, this also means that there is a lack of firm consensus among the ichnologist, including the present authors as

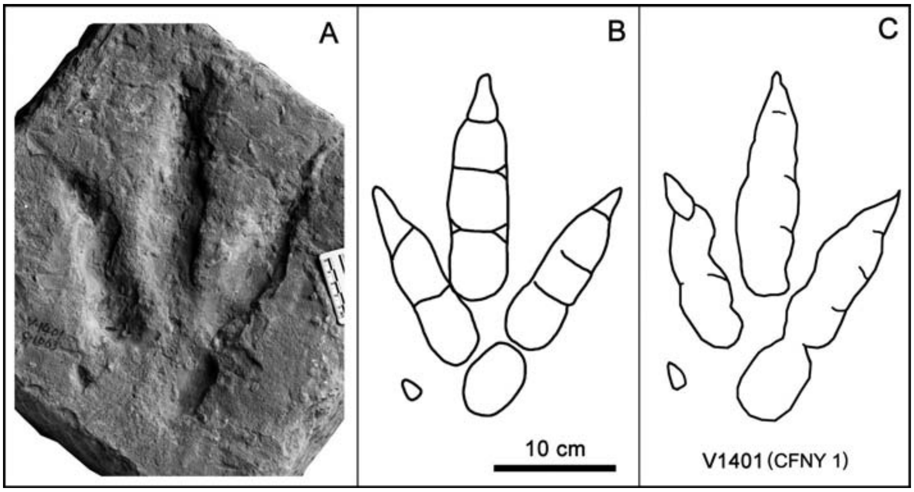

Fig. 6 *Chongqingpus nananensis* V1401 (CFNY 1, type)
A. Photographs; B. Drawing by Yang and Yang (1987); C. Our drawing of the same specimen. Compare with Fig. 4

to the taxonomic status of *Chongqingpus nananensis*, as there has also been uncertainly about the status of other ichnospecies in genus *Chongqingpus* (Lockley et al., 2003; Lockley and Matsukawa, 2009).

The mean length/width ratio calculated from V1401, V1394-5, V1394-6, and ZLJ T1 is 1.4. Track V1401 exemplifies the *C. nananensis* morphology. The axis of the putative hallux impression is nearly parallel to the digit II impression, and the angle between the midline of the hallux and the track axis is 26°. Digit III projects the farthest cranially (anteriorly), followed by digits II, IV, and, if indeed present, I. The deep, concave digit impressions retain pad impressions that seem to have a formula of 1?-2-3-4-x. The metatarsophalangeal pad (pad 1) and pad 2 of digit IV possess an indistinct interpad space. Each digit has a sharp claw mark, and digit II has the clearest and longest. In general, the digits have wide divarication angles (53°–57°).

V1394-5 and V1394-6 (Figs. 4, 7) are left footprints. The major, characteristic similarities between V1394-5, V1394-6, and V1401 are summarized in Table 1. In V1394-5, a possible hallux trace is approximately parallel to the impression of digit II, the pad traces are weakly discernible in digit II and digit III, the digit IV trace shows four pad impressions, and the lateral margin of the digit IV impression is relatively shallow (Fig. 7B, indicated by gray region). This shallow digit IV impression may record slippage or sliding by the track maker. Digit IV reveals a shallow outer trace parallel to the main deeper part of the trace. The shallow trace diverges laterally by about 5°. Furthermore, digit IV impression is apparently deeper than other digits. V1394-6 lacks a digit I print, has an indistinct claw trace on digit II (Fig. 4), and has a fusiform impression of digit III with both a proximal and a distal pad. For all tracks, digit IV is generally deeper than digit II.

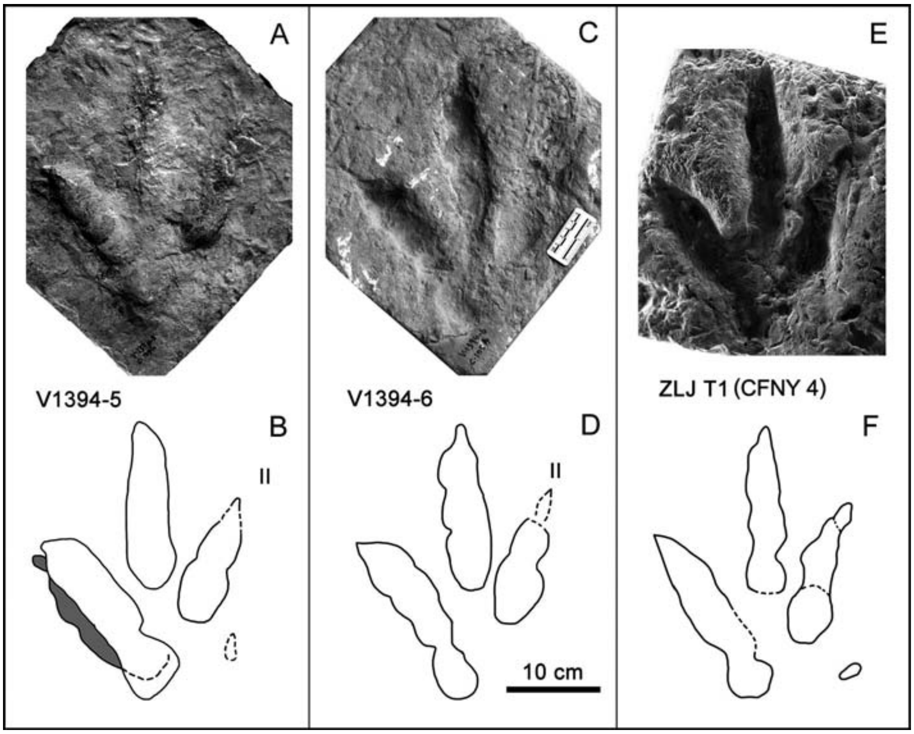

Fig. 7 *Chongqingpus nananensis* V1394-5, V1394-6 and ZLJ T1 (CFNY 4)
A, C, and E. Photographs; B, D, and F. Our drawing. Compare with Fig. 4

The depth of ZLJ T1—the cast of the morphotype CFNY 4—is at least twice that of the other three observed tracks and is also greater than the depth reported by Yang and Yang (1987). We cannot exclude the possibility of artificial deepening by the museum of World Dinosaur Valley Park for exhibition purposes based on comparison between the replica of the holotype (ZLJ T1) and the photograph of CFNY 4 (compare Fig. 7 with Yang and Yang (1987: plate III-2). However, the outline of the track should reflect its basic morphology, and the main characteristics of ZLJ T1 are strikingly similar to those of V1394-6 except that the position of the putative hallux impression differs from those of V1401 and V1394-5. In ZLJ T1, the axis of the inferred hallux impression is not parallel to the impressions of either digit II or III. Rather the angle between the hallux and the track axis is 58° degrees.

3.1.3 Comparisons between *Chongqingpus nananensis* and other morphotypes

As indicated above (Figs. 3-7), there are numerous topotype specimens of *Chongqingpus nananensis*. This is in addition to the complicating factor that Yang and Yang (1987) named two other ichnospecies of *Chongqingpus*: the small tracks *C. microiscus* and *C. yemiaoxiensis*. However, both these morphotypes are quite distinct from *C. nananensis*, and both are assignable to the ichnogenus *Grallator* (as *G. microiscus* and *G. yemiaoxiensis*: cf. Lockley et al., 2003; Lockley and Matsukawa, 2009; Lockley et al., 2013). The lengths of

C. microiscus and *C. yemiaoxiensis* are 14.5 and 17.8 cm, respectively—proportions that are consistent with the *Grallator* morphotype (Olsen et al., 1998). However, while Yang and Yang (1987) reported *C. yemiaoxiensis* from the Nan'an tracksite in the Xiashaximiao Formation, *C. microiscus* originates from a different horizon (the Xintiangou Formation) and locality (the aforementioned Wumacun Site B). However, the stratigraphic interpretation of Nan'an tracksite now suggests it pertain to the middle Shangshaximiao Formation (Wu et al., 2003; Liu et al., 2006). This leads to the conclusion that *Grallator* occurs in the Ziliujing Formation and both the Xiashaximiao and Shangshaximiao formations, which is unsurprising given the ubiquity of that ichnogenus globally in the Jurassic.

As suggested by Gierliński (1994), Lockley et al. (2003, 2013), Lockley and Matsukawa (2009), and Xing et al. (2009a), there are many problems associated with attempts to classify Jurassic theropod tracks. Lockley et al. (2013) concluded that the only five of the 20 named ichnogenera from the Early and Middle Jurassic of China are valid: *Eubrontes*, *Grallator*, *Gigandipus*, *Kayentapus*, and *Changpeipus*. These authors provisionally recognized only *Jialingpus* and *Yangtzepus* as valid, Late Jurassic, Chinese ichnogenera based on Chinese types, but note that the former is *Grallator*-like and the latter similar to *Therangospodus*. Xing et al. (2011a) recognized the ichnogenera *Therangospodus* and *Megalosauripus* in the Late Jurassic of China.

Lockley et al. (2013) suggested that *C. nananensis*, should be synonymized at the ichnogenus level with *Kayentapus*. However, one of us (JL), is conducting further studies on Chinese theropod tracks and holds that, due to the presence of the hallux it may be possible to retain the ichnospecies *C. nananensis*, already reduced to a monospecific ichnogenus by transfer of the other two *Chongqingpus* ichnospcies to *Grallator*. Although the option to retain *C. nananensis* as a valid ichnospecies, rather than a synonym of *Kayentapus* is not discounted by other authors of this paper, Lockley et al. (2013) have made attempts to address the problem of over-split theropod ichnotaxa. Such alternative options are not easily resolved, especially in the case of the *C. nananensis* sample which has only a few specimens with purported hallux traces. As noted below, even the classic literature on *Eubrontes* allows for occasional hallux traces, without necessarily changing the ichnotaxonomic label. One characteristic of the type specimen (consisting of five tracks) of *Kayentapus* (*K. hopii*), described by Welles (1971) and recently re-described by Lockley et al. (2011), is that its tracks consistently show the metatarsophalangeal pad of digit IV well separated from the rest of the digit impressions. *K. hopii* is slightly larger (foot length 34 cm) than the Nan'an (*C. nananensis*) morphotype (foot length ~29 cm). However, type *Kayentapus* tracks lack halluces according to Welles (1971). The importance of hallux impressions as diagnostic features of theropod tracks is debatable. In cases where the hallux is well developed and appears consistently in multiple tracks (e.g., in *Gigandipus* or *Saurexallopus*), the size of the hallux (and, often, position) is diagnostic. However, in cases where the hallux trace is inconsistent or ambiguous, its diagnostic utility is questionable. For example, the type specimen of *Eubrontes* has no hallux, but in rare cases hallux traces have been reported (see Milner et al., 2006 for discussion). The Nan'an sample is a case of the latter phenomenon: their ostensible hallux traces are small and occur only in a few examples, some of which are ambiguous. However, they appear to be present in the paratype (CFNY 4) and the holotype (CFNY 1). In general, *C. nananensis* specimens may best be accommodated in ichngenus *Kayentapus*.

Some of the present authors consider the *C. nananensis* morphotype similar to *Megalosauripus* based on certain characteristics. For one, elongate "heel", relative to the length of digit III impression (cf. Lockley et al., 1998: fig. 8), the lengths of the digit III impressions average 62% of the total footprint length; in *Megalosauripus*, the average is 60%. Second, the proximal edge of phalangeal pad 1 on digit III is anterior to the posterior edge of the second phalangeal pad on digit IV (Lockley et al., 1998). However, North American *Megalosauripus*, the only substantial measured sample, is a much larger morphotype (footprint length ~41–50 cm), which lacks a hallux (Lockley et al., 1998). Thus, the sporadic occurrence of a small hallux trace in the *C. nananensis* morphotype also differentiates it from *Megalosauripus*. We infer that the *C.nananensis* trackways were narrow, based on Yang and Yang (1987: fig. 8). This again suggests differences from *Megalosauripus* trackways, which are typically wider (Lockley et al., 1998).

3.2 Theropod tracks from the Jinji tracksite

Material, locality, and horizon Nine complete natural molds of pes prints, cataloged as JJ1–9 (Fig. 8; Table 1), in a trackway from the Upper Jurassic Shangshaximiao Formation of the Jinji tracksite, Yongchuan District, Chongqing, China. The original tracks remain in the field.

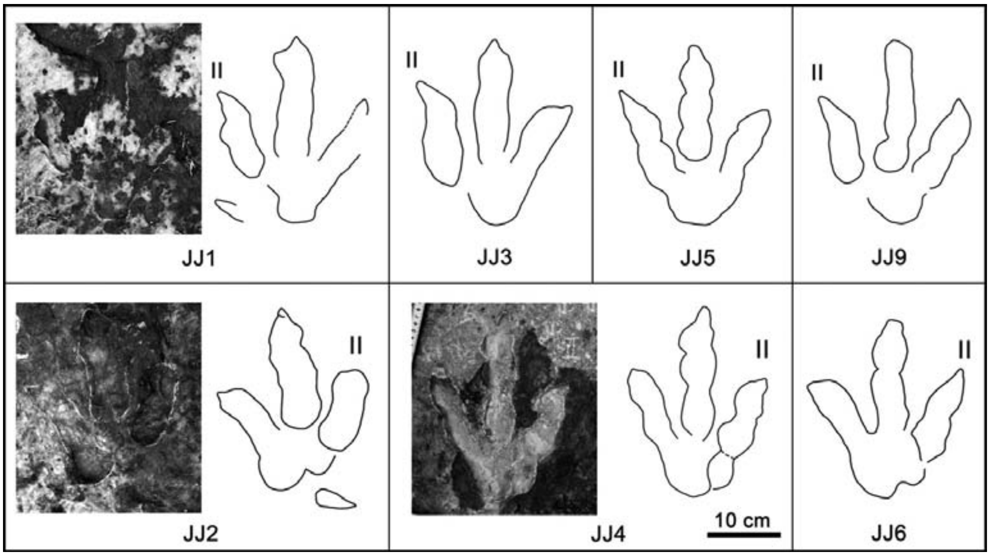

Fig. 8 Photographs and our drawing of the Jinji tracks JJ1–JJ6 and JJ9

Table 1 Measurements of the best-preserved medium-sized theropod tracks from Jinji and Nan'an tracksites (cm)

Number	R/L	ML	MW	LD I	LD II	LD III	LD IV	II-III	III-IV	II-IV	SL	PL	PA	L/W
JJ1	R	25.7	20.4	4.9	13.1	17.1	11.3	31°	30°	61°	187.5	93.5	169°	1.3
JJ2	L	25.1	19.6	5.7	11.5	17.1	10.0	32°	33°	65°	195.2	94.8	169°	1.3
JJ3	R	25.5	21.8	—	15.2	17.6	11.1	28°	33°	61°	195.5	101.3	165°	1.2
JJ4	L	26.3	18.7	—	11.5	18.9	11.8	28°	29°	57°	190.0	95.8	160°	1.4
JJ5	R	24.9	20.8	—	15.5	16.2	10.4	27°	35°	62°	—	97.0	—	1.2
JJ6	L	24.7	21.6	—	13.7	15.7	10.7	27°	36°	63°	—	—	—	1.1
JJ9	R	25.2	19.4	—	12.6	18.3	12.4	31°	26°	57°	—	—	—	1.3
V1401	R	28.5	19.1	2.4	15.2	18.3	22.1	24°	29°	53°	—	—	—	1.5
V1394-5	L	29.7	21.7	2.8	14.1	18.0	20.0	25°	32°	57°	—	—	—	1.4
V1394-6	L	29.1	21.4	—	15.1	18.0	20.3	23°	33°	56°	—	—	—	1.4
ZLJ T1	L	29.0	21.4	2.7	16.0	18.0	20.8	24°	34°	58°	—	—	—	1.4

Abbreviations: R/L. right/left; LD I–IV. length of digit I–IV; ML. maximum length; MW. maximum width (dinosaur tracks measured as distance between the tips of digits II and IV); PA. pace angulation; PL. pace length; SL. stride length; II-III, III-IV, II-IV. angle between digits II and III, III and IV, II and IV respectively; L/W. maximum length/maximum width.

Description JJ1–6 and JJ9 are medium-sized (range of print length 24.7–26.3 cm), functionally tridactyl theropod tracks, cigar-shaped digital impressions, the tracks with supposed hallux traces are poorly preserved, only faintly visible on JJ1 and JJ2. Due to the positioning of a wooden walkway erected over the JJ7 and JJ8 portion of the trackway, these two tracks are recognizable but difficult to measure. Manus and tail traces are not present. These tracks compose a clear trackway that is 7.9 m long.

For the convenience of comparison, we used the methods of Olsen et al. (1998: fig. 3, different methods to Table 1) to measure the tracks. The lengths of the well-preserved digits II-III-IV of JJ4 are 6.3, 10.2, 12.4 cm respectively, producing ratios of III/II = 1.62 and III/IV = 0.83.

JJ1, 3, 5, and 9 are right footprints. The length/width ratios of these four tracks range from 1.2–1.3. JJ1 has a hallux impression, the angle between the midline of hallux and track axis subtends an angle of 62°. The medial margins of digits II and III are weathered or otherwise suffer from deformation. The lateral margin of the digit IV trace is weathered, and discrete borders separate the metatarsophalangeal region from the proximal end of digit II (but not III and IV). Claw marks and digit pad impressions are present but indistinct. The terminal metatarsophalangeal region is U-shaped, and the metatarsophalangeal region lies nearly in line with the axis of digit III. With the exception of the hallux impression and the weathered digits, characteristics of JJ1 are similar to those of JJ3. Digits II and III of JJ5 are well-preserved, with faint indentations at the margins of the pads, suggesting two and three pads, respectively. The claw mark of digit II is sharp, but that of digit III is blunt. Discrete borders separate the metatarsophalangeal region from the proximal end of digit III (but not II and IV), unlike in JJ1. The proximal of metatarsophalangeal region exhibits a parabolic curve. Other characteristics of JJ5 are similar to those of JJ1. Except for digit III and the first proximal pad of digit IV, the digit pads of JJ9 are faint, and discrete borders separate the metatarsophalangeal region from the proximal ends of digits II and III, but not IV.

JJ2, 4, and 6 are left footprints. The length/width ratios of these tracks range from 1.1–1.4. JJ2 also has a hallux impression, but each digit is poorly preserved, the midline of hallux and track axis subtends an angle of 104°, discrete borders separate the metatarsophalangeal region from the proximal ends of digits II and III, but not IV. Claw marks are sharp and indistinct; digit pad impressions are likewise indistinct. The metatarsophalangeal region lies nearly in line with the axis of digit III and is divided into medial and lateral parts: a larger pad associated with digits III and IV, and a smaller (approximately half as large as the other) pad associated with digit II. Digits II and III of JJ4 are well preserved, with two and three digit pads, respectively. Only two pads of digit IV are discernible. The border between the metatarsophalangeal pads of digit II and IV are distinct. Other characteristics of JJ4 are similar to those of JJ2. JJ6 is heavily weathered, but similar to JJ4 in general morphology.

Overall, the divarication angles between digits II and III of JJ1–6 and JJ9 are smaller than those between digits III and IV, and the divarication angles between digits II and IV are 57°–65°. Digits II and IV of the Jinji tracks slope outward. This slope closely resembles that of the Late Jurassic theropod tracks described by Milàn et al. (2006). Pace angulation measurements of the trackway are 160°–169°.

In morphology, the Jinji tracks differ from the *C. nananensis* morphotype in the following characteristics: smaller overall size (the Jinji tracks average 25.3 cm long, while the *C. nananensis* specimens average 29.1 cm); elongate "heel", relative to the length of digit III impression (cf. Lockley et al., 1998: fig. 8), the lengths of the digit III impressions average 68% of the total footprint length. The digit pads discerned on digit II and III.

Comparisons and discussion The Jinji tracks are superficially similar to *Therangospodus* in that both are medium sized, have elongate, cigar-shaped digital impressions that are not separated by creases, have narrow trackways with pace angulations averaging ≈166° (170° in *Therangospodus*; Lockley et al., 1998), and have variable pace lengths, averaging 96 cm (94 cm in *Therangospodus*; Lockley et al., 1998). The phalangeal pads of *Therangospodus* are discernible. Lockley et al. (1998) indicated that faint indentations at the margins of pads sometimes reveal the location of phalangeal pads and suggested that *Therangospodus* had a 2-3-4 phalangeal formula. The phalangeal pad formula of Jinji tracks is discernible; however, they have faint hallux impressions, rare among non-avian theropod tracks. The Jinji tracks also differ from *Therangospodus* in having a trackway width averaging 31.9 cm (n = 4), less than *Therangospodus* (35 cm, n = 29)(Lockley et al., 1998).

However, all Jurassic theropod tracks are quite similar in general morphology (Lucas, 2007). The "fleshiness" and lack of discrete pad traces in tracks that are weathered and poorly-preserved may make them look more like *Therangospodus* than the case if preservation were better. For example, tracks JJ4 and, to a lesser extent, JJ5 (Fig. 8) differ from *Therangospodus* and are more like small *Eubrontes*, *Grallator*, or *Kayentapus*. The metatarsophalangeal pads of digits II and IV in the right footprints of the Jinji tracks are very similar to *Eubrontes* isp. AC 45/1 (Lull, 1904, 1915, 1953). Olsen et al. (1998) suggested that this was due to a partial collapse of the sides of the deeper track when the foot was withdrawn. However, in the Jinji tracks, only the right tracks exhibit distinct metatarsophalangeal pads, while the metatarsophalangeal regions of the left tracks are indistinct (though present). This may be attributable to depositional factors, or it might be that, while walking, the maker of Jinji tracks favored to place the greater weight on the right foot, producing deeper, more distinct right tracks. However, when used the methods of Olsen et al. (1998: fig. 3) to measure, the ratios of III/II and III/IV (1.62 and 0.83, respectively) are higher than those of *Eubrontes giganteus* (1.32 and 0.81, respectively, in AC 15/3). The greater divarication angles of digits II and IV (57°–65°) also differ from those of *Eubrontes* (25°–40°).

Because possible hallux traces only occur in two tracks (JJ1 and JJ2), we again have a situation where the majority of tracks representing this morphotype do not show hallux traces. Thus, as noted above, the Jinji tracks lack the continuous appearance and well-defined medially or caudomedially oriented hallux trace of *Gigandipus* (Milner et al., 2009). The Jinji tracks are more robust, and have smaller divarication angles (57°–65° vs. 60°–72°), than the *Kayentapus* morphotype (Lockley et al., 2011). Compared to *Jialingpus* (Zhen et al., 1983), the Jinji tracks are larger (24.7–26.3 cm vs. 9.8–23.8 cm) and have smaller length/width ratios (1.1–1.4 vs. 1.76–2.29)(Xing et al., 2011b). Thus, the more comparisons that are made, the more subtle similarities and differences we simultaneously find between the Jinji tracks and the various morphotypes (*Eubrontes*, *Grallator*, *Kayentapus*, *Gigandipus*, *Therangospodus*, and *Megalosauripus*) known from the Jurassic. This underscores the basic similarities and the conservative nature of the theropod foot.

Late Jurassic assemblages of theropod tracks assignable to or comparable to the ichnogenera *Megalosauripus* and *Therangospodus*, as diagnosed in North America, have been reported from Europe and central Asia, and are apparently restricted to or most abundant in the Oxfordian-Kimmeridgian boundary interval (Lockley et al., 1998). It is tempting to infer, based on size, stride and age, that the Jinji tracks are like *Therangospodus*. However, although it is possible to make useful stage- or age-level ichnostratigraphic correlations when distinctive and demonstratively similar tracks occur in coeval strata, it is not advisable, or helpful, to do so when the tracks being compared show some of the significant differences as noted here. The results, therefore, are inconclusive: the Jinji tracks have some of the characteristics of the medium-sized theropod ichnogenus *Therangospodus*, but are not close enough to be assigned to that ichnogenus with confidence; herein we tentatively labeled the Jinji tracks as cf. *Therangospodus*.

4 Track makers

In the Chongqing area, only one genus of Shangshaximiao Formation theropod is known: *Yangchuanosaurus*. There are three *Yangchuanosaurus* fossil sites (Fig. 9), one of which produced remains of *Y. shangyouensis* (Dong et al., 1978), one *Y. magus* (Dong et al., 1983), and one an as-yet undescribed species of *Yangchuanosaurus* from Nan'an (Chongqing Evening Paper, May 31, 2010). *Yangchuanosaurus* is a large sinraptorid (body length of 7–10 m)(Peng et al., 2005).

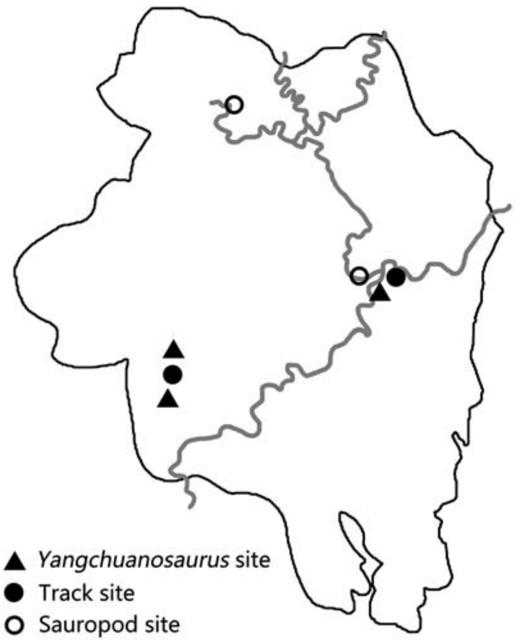

Fig. 9 Distribution of *Yangchuanosaurus*, theropod track and sauropod skeletal sites in west Chongqing

However, there are at least three distinct theropod track morphologies occurring in Chongqing: *Grallator*, *Kayentapus*, and cf. *Therangospodus*; the latter two are described here. The body length of the track maker of the cf. *Therangospodus*, calculated using the average hip height to body length ratio of 1:2.63 (Xing et al., 2009b) and the formula: hip height ≈ 4 × footprint length (Henderson, 2003), is approximately 2.6–2.8 m. The body length of the track maker of *Kayentapus* is approximately 3 m. In terms of body length, the Jinji and Nan'an track makers differ from known specimens of *Yangchuanosaurus* (or other sinraptorid theropods). This estimated size discrepancy suggests the tracks were either made by juvenile *Yangchuanosaurus* or suggests richer theropod diversity than is currently inferable from the skeletal fossil record alone.

5 Conclusions

A large sample of theropod tracks from the Nan'an site in the heart of Chongqing Municipality is described and compared with a newly reported trackway from the Jinji site. The Nan'an material, previously assigned to *Chongqingpus*, is well-preserved and allows a more detailed description of the material than was previously presented by Yang and Yang (1987). These theropod tracks are *Kayentapus* and co-occur with *Anomoepus*-like tracks. The Jinji tracks are tentatively compared with *Therangospodus*, and both assemblages are inferred to be Upper Jurassic Shangshaximiao Formation.

Despite the steady increase in reports of theropod tracks from the Jurassic of southern China, the exact age of track-bearing formations, their correlation, and the identification of ichnospecies and ichnogenera remains difficult and not universally agreed. Thus, assemblages with typical Lower Jurassic forms (*Grallator*, *Kayentapus* and *Anomoepus*) evidently persist in Middle and Upper Jurassic formations. This means that theropod tracks cannot presently be used to differentiate Lower, Middle and Upper Jurassic units. However, although not ichnostratigraphically useful, this is a positive result, because it indicates that ichnofaunas were theropod-dominated in the region throughout the Jurassic, and may even have persisted with this general composition into the Cretaceous (Matsukawa et al., 2006). Further work is required to define and date the Jurassic stratigraphy of the region, describe well-preserved, theropod-dominated ichnofaunas in detail, identify the ichnotaxa present with confidence, and tie these into the stratigraphic sections accurately.

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重庆晚侏罗世两处兽脚类足迹组合与四川盆地侏罗纪地层

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摘要：重庆市已报道了4处侏罗纪的恐龙足迹点，包括下侏罗统珍珠冲组的大足化石点，该地点发现了中国迄今最古老的蜥脚类行迹；另外两处化石点(南岸和金鸡)的层位曾被视为中或上侏罗统，这里首次将其确认为上侏罗统上沙溪庙组；第4处化石点(成渝)，本

文全部作者目前都未曾观察，这里不做描述。南岸化石点是南岸重庆足迹(*Chongqingpus nananensis*)模式标本的所在地，位于重庆市中心，曾发现过大量兽脚类足迹，如今已消逝在城市化进程中。幸运的是，这批标本被保存于重庆自然博物馆，本文作者曾前后两次对其进行研究，并得出文中的结论。南岸重庆足迹为中型足迹(平均长约29 cm), 最可能被卡岩塔足迹(*Kayentapus*)所囊括，这批标本中有一些保存着边界不清的拇趾迹。该化石点的其他足迹被归于似异样龙足迹(cf. *Anomoepus*)。其他较小的、来自重庆市周边中侏罗统中部的足迹此前已被归于跷脚龙足迹(*Grallator*)。金鸡化石点保存了一条孤立的兽脚类行迹，因其粗壮的特征而被暂时归于似窄足龙足迹(cf. *Therangospodus*)。金鸡点的行迹也保存了非连续出现的拇趾迹。虽然重庆市和四川盆地及其周边更广泛地区之侏罗纪地层发现的兽脚类足迹日渐增多，但要明确其确切地质年龄及有效的足迹分类依然需要进一步工作。这是因为侏罗纪的恐龙足迹尽管丰富，但显示出连续变化的形态学特征，而保存状况的变化更使其难以在时间与空间上做出定义与鉴别。

关键词：重庆，四川盆地，晚侏罗世，兽脚类足迹，足迹分类学

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